PROF. SCHEMBERG

MEASUREMENT UNDERSTOOD THROUGH THE QUANTUM POTENTIAL APPROACH

D. Bohm and B. Hiley, Birkbeck College, University of London

ABSTRACT

We review briefly the quantum potential approach to the quantum theory, and show that it yields a completely consistent account of the measurement process, including especially what has been called the "collapse of the wave function". This is done with the aid of a new concept of active information, which enables us to describe the evolution of a physical system as a unique actuality, in principle independent of any observer (so that we can, for example, provide a simple and coherent answer to the Schrödinger cat paradox).

Finally, we extend this approach to relativistic quantum field theories, and show that it leads to results that are consistent with all the known experimental implications of the theory of relativity, despite the non-locality which this approach entails.

1. Introduction

In two earlier papers[1,2], an alternative to the usual interpretation of the quantum theory was proposed, based on the notion of a particle acted on by a new kind of field that gives rise to what was called a quantum potential. It was shown that this led to a generally consistent approach, which enables one intuitively and imaginatively to understand how quantum processes may actually come about, through the movement of the particle under the action of this quantum potential.

This approach has not generally been adopted by the community of physicists, perhaps mainly because it did not lead to any new predictions for actual experimental results. It was not that it could not in principle do so, but rather, the further hypothesis needed for this purpose seemed rather arbitrary, because there were no experimental clues or indications that could serve to limit them in a significant way[3].

In addition, there was perhaps a misunderstanding as to the intention behind the suggestion of this interpretation. Its purpose was not to suggest that the ideas in it were to be regarded as a final and received version of the ultimate nature of reality. Rather, it was proposed in the spirit of a provisional point of view, that would help provide further insight into the significance of the quantum theory, a kind of insight that is made possible by the intuitive and imaginative way in which it shows the meaning of the mathematical equations[4]. Thus, with the aid of this and other interpretations, it would be possible to understand the theory more thoroughly and deeply than would be possible with one interpretation alone.

We begin by summarizing briefly the main features of the quantum potential interpretation. First of all, in the one-body system, it was shown that it can explain all the peculiar new features of the quantum behavior of matter (for further details as to the trajectories of the particle under the action of a quantum potential, see Philippidis et al[4][5], Dewdney and Hiley[6]). The one-body treatment was very similar to that of de Broglie[7]. However, in the many-body system, a number of crucial new features emerged[8]. Firstly, the interaction of particles with each other was now non-local, and secondly, it was not fixed once and for all, but in general determined by the "quantum state" of the whole system. Thus, the classical mode of analysis of a system into separate parts whose relationships are independent of the state of the whole is no longer generally valid. Rather, separable and independent parts were now seen to be a special and contingent feature, which is dependent on the whole in a way that cannot even be described in terms of the parts alone. In this respect, the theory was in agreement with the approach of Bohr[9], but the key difference was that the quantum potential interpretation provided a physical notion of how this wholeness may be brought about, through the actual movement of independently existent particles under the action of the quantum potential, whereas in Bohr's formulation, such questions are expressly ruled out as having no meaning.

The treatment of the measurement problem was a particularly significant application of the new interpretation. It was shown that during the course of a measurement, the quantum potential acting on the observed particle depends not only on the position of the particle, but also on the positions of all the particles constituting the measuring apparatus. As a result, the observed particle suffers a disturbance that is unpredictable and uncontrollable (in essence, because the particles constituting the apparatus, which evidently are not observed, are moving with random thermal motions). Heisenberg's uncertaintly relations were shown to follow from this disturbance. (Indeed, this sort of model comes close to what was implied in Heisenberg's original formulation of the uncertainty principle, which tacitly discussed the solution in terms of a particle with a definite but unknown trajectory, which also was subject to an unpredictable and uncontrollable disturbance.)

In addition, a consistent treatment was given of what is, in the usual interpretation, called the "collapse of the wave function". To see the nature of the problem involved here, we first consider the fact that in a classical field, all wave packets exist <u>together</u> in a single three-dimensional space. But the quantum wave function is in a 3-N dimensional configuration space, and only one of the packets can be actual after the experiment (i.e., the packets then exclude each other). It is the requirement of having only a single packet when the measurement process is completed that leads us to say that the wave function appears to "collapse" in a way that violates Schrödinger's equation.

A particularly vidid example of what is meant here is given by the well known Schrödinger cat paradox. One says that an observation causes the wave function to "collapse" either to one representing a live cat or to one representing a dead cat. It then appears at first sight that the question of whether the cat is alive or dead is decided ultimately by the content of the consciousness of an observer. Indeed, Wigner[10] proposes that this is in essence just what happens. However, Everett[11] has given an interpretation in which both the "collapse" and the dependence of the result on the consciousness of an observer are avoided. In this interpretation there is a multiplicity of universes. Some of these contain a live cat and a physicist who observes a live cat, while others contain a dead cat and a physicist who observes a dead cat. However, as Bell[12] points out, this is an extreme case of a lack of economy of concepts, involving the assumption of a non denumerable infinity of universes, with a corresponding non-denumerable infinity of observers within them. Can this question be cleared up without the activity of the consciousness of an observer in a typical measurement, as carried out in physics, and without bringing in the notion of a non-denumerable infinity of universes that are not observable to us? We do this in the quantum potential interpretations by showing that all the packets of the multi-dimensional wave function that do not correspond to the actual result of the measurement have no effect on the particle, not only at the moment immediately after its interaction with the measuring apparatus is over, but also for all times from then on (this is seen to follow from the irreversibility of the random thermal motions of the particles constituting the apparatus). And so, such packets can be dropped from further discussion.

It is perhaps not generally realized that all such problems of principle arising in the formulation of the quantum theory can be dealt with adequately in terms of the quantum potential interpretation. However, the treatment given earlier is, in certain important respects, too condensed to show this directly (though it was there implicitly). Therefore, we feel that a more extensive treatment is called for, which we shall give in this paper.

We also include in this paper a discussion of the quantum mechanical field theory. To do this, we bring in what we call the super-quantum potential, which acts on the whole field over the entire universe and bring out how, through its action, a consistent extension of this interpretation can be obtained.

What is perhaps more interesting is that if the quantum field theory is covariant in the usual sense, the interpretation can also be seen to be consistent with the experimental implications of the theory of relativity, despite the non-local instantaneous interactions brought about by the quantum super-potential. This result is particularly relevant in relationship to the latest experimental results of Aspect et al[13], who has given evidence favoring the assumption that non-local quantum correlations hold, even for measurements occurring outside each other's light cones.

2. Quantum Potential as Active Information

We now review in more detail the main features of the quantum potential approach, but emphasize its significance in terms of our new concept of active information.

We begin with the Schrödinger equation for a single particle.

$$i\hbar \frac{\partial\psi}{\partial t} = \frac{-\hbar^2}{2m}\nabla^2\psi + V\psi \qquad (1)$$

We write

$$\psi = Re^{iS/\hbar}, \qquad P = R^2$$

and obtain

$$\frac{\partial P}{\partial t} + \mathrm{div}\left(P\,\frac{\nabla S}{m}\right) = 0 \qquad (2)$$

$$\frac{\partial S}{\partial t} + \frac{(\nabla S)^2}{2m} + V + Q = 0 \qquad (3)$$

$$Q = \frac{-\hbar^2}{2m}\frac{\nabla^2 R}{R} \qquad (4)$$

As brought in the previous papers[1,2][8][14], the basic assumption is that the electron <u>is</u> a particle, with a definite coordinate, $\vec{X}$, that is a well defined continuous function of the time. Its velocity is assumed to be given by

$$\vec{V}(X_1 t) = \frac{\nabla S(\vec{X},t)}{m}$$

The function, S, satisfies eqn. (3), which is equivalent to a modified Hamilton-Jacobi equation, containing not only the classical potential V, but also the quantum potential, Q, given by eqn. (4). (To calculate the quantum potential, one has to solve Schrödinger's equation for ψ, and then insert $R = \sqrt{\psi^*\psi}$ into (4).) In effect, we are assuming that the Schrödinger ψ represents a physically real field, that is capable of acting on the particle through its determination of the quantum potential.

Finally, we assume that $P = R^2$ is the probability distribution of particles in a statistical ensemble of similar systems. The consistency of this assumption is guaranteed by the eqn. (2). However, it has been shown[3] that one may assume that $\vec{V} = \frac{\nabla S}{m}$ is only the average velocity in a stochastic process, in which $P = R^2$ is the limiting distribution after allowing a sufficient period to establish random diffusion. But it is important to note that no matter how we explain this distribution, it is assumed to represent a situation that actually exists independently of any act of observation or measurement. Indeed, as pointed out earlier, the statistical fluctuations in the results of measurements will ultimately follow from the statistics of the distributions of particles. This is a contrast to what happens in the usual interpretation, in which the statistics refer essentially to the results of measurements only.

For various historical reasons, the notion of "hidden variables" was introduced in the earlier papers[1,2]. This was perhaps unfortunate. For as pointed out by Bell[12], there is nothing "hidden" about the particle variables. Rather, the main new point is that these variables are acted on by a quantum potential. This potential is different in many ways from classical potentials. But such differences are needed, if we are to account for the quantum properties of matter, which are so different from its classical properties.

The first key difference is that multiplication of the wave function by a constant does not change the quantum potential. The quantum potential can therefore still be large even when the wave function is small. This means that its affects do not necessarily fall off with the distance. For example, in the two-slit experiment(5) a complex pattern of plateaux and valleys appears in the quantum potential. This directs a random distribution of incident particles to form fringes, even far from the slits.

An essential new feature of the quantum potential is therefore that only the form of the Schrödinger ψ field counts, and not the intensity. So the force arising from this potential is not like a mechanical force of a wave pushing on a particle with a pressure proportional to the wave intensity. Rather, it acts more like an information content (recall that "to inform" means literally "to form within"). We may make an analogy here to radar waves that guide a ship. These do not push the ship mechanically. If the ship is on automatic pilot it may then be regarded as a self-active system, with its activity directed by radar waves containing information about the whole surroundings. Similarly, one may think that the electron is self-active in a new way, dependent on what we shall from now on call the quantum information potential, Q.

Of course, we do not regard this as a final or definitive explanation. Rather, as pointed out earlier, we feel that to look at the theory in this way gives a further insight into the new features of matter as implied by the quantum theory, which are either obscure or inaccessible to our cognizance in the absence of such an explanation.(footnote I)

In particular, one of the main new insights is that one can see how distant features, such as slits, can still be basically significant in determining the motion of an electron. Or to put it differently, it may be said that we can now understand how even in the one-body system, there is already a certain kind of non-locality (though it is explained by a purely local propagation of active information in the Schrödinger ψ field from the whole environment of the electron). And this shows clearly the inseparable wholeness of the over-all experimental situation, in which the meaning of the experimental results (e.g., fringes) cannot be understood apart from the total set of experimental conditions (e.g., slits), which contribute to the quantum information potential even at long distances. As pointed out earlier, this is along the lines of Bohr's formulation, which also emphasizes, though in a different way, the inseparable wholeness of observed system and the experimental arrangement that is its environment.

Clearly, the quantum potential interpretation is to be distinguished from a hydrodynamic model (such as that of Madelung[15]). For in this model, the particle is simply pushed mechanically by the fluid. The notion of a particle responding actively to information in the ψ field is indeed far more subtle and dynamic than any others that have hitherto been supposed to be fundamental in physics. This is especially evident, as we shall see, in the many-body system, for which simple models, such as the hydrodynamical one, can no longer be applied at all. The choice therefore seems to be either to bring in entirely new principles in the description of physical process, or to assume that nothing at all can be said in the way of explaining the quantum behavior of matter. In particular, we are here emphasizing that the requisite new principles involve the notion that a particle responds actively to information (or alternatively, that information is active, even at the most fundamental levels treated by physics).

We shall now go on to consider the many-body system with its wave function, defined in the configuration space of N particles, $\Psi = \Psi(\vec{X}_1, \vec{X}_2 \ldots \vec{X}_N, t)$.

We shall begin by considering two bodies.
The wave function, $\psi(\vec{X}_1, \vec{X}_2, t)$ satisfies the Schrödinger equation

$$i\hbar\frac{\partial\Psi}{\partial t} = \left[-\frac{\hbar^2}{2m}(\nabla_1^2 + \nabla_2^2) + V\right]\Psi \qquad (5)$$

where ∇_1 and ∇_2 refer to particles 1 and 2 respectively.
Writing $\psi = Re^{iS/\hbar}$ and defining $P = R^2 = \Psi^*\Psi$, $\vec{v}_1 = \frac{\nabla_1 S}{m}$ and $\vec{v}_2 = \frac{\nabla_2 S}{m}$
we obtain

$$\frac{\partial P}{\partial t} + \text{div}_1\left(P\frac{\nabla_1 S}{m}\right) + \text{div}_2\left(P\frac{\nabla_2 S}{m}\right) = 0 \qquad (6)$$

$$\frac{\partial S}{\partial t} + \frac{(\nabla_1 S)^2}{2m} + \frac{(\nabla_2 S)^2}{2m} + V + Q = 0 \qquad (7)$$

$$Q = \frac{-\hbar^2}{2m}\,\frac{(\nabla_1^2 + \nabla_2^2)R}{R} \qquad (8)$$

As in the case of the one body system, the assumption that $P(\vec{X}_1, \vec{X}_2)$ represents the probability density in the configuration space of the two particles is consistent, because of the conservation equation (6), and because, in principle, one could define a stochastic process in which this probability would come about as an equilibrium distribution under random diffusion.

The quantum potential, $Q(\vec{X}_1, \vec{X}_2, t)$ now depends on the positions of both bodies in a way that does not necessarily fall off with the distance. We thus obtain the possibility of non-local connections. Going on to consider an N-body system, we will have $Q = (\vec{X}_1 \ldots \vec{X}_N, t)$ so that the interaction of each pair of particles may then depend non-locally on all the others, no matter how far away they may be.

A still more important novel feature, however, is that Q is a function of ψ, which depends on the state of the whole system and, as mentioned earlier, this dependence cannot be expressed in terms of the locations of the particles constituting the system. That is to say, the relationships of particles are not pre-assigned functions of the distance, but rather, vary according to the "quantum state" of the whole system. This is a much stronger notion of wholeness than we have had before. Such behavior of a quantum system is reminiscent of that of an organism, in which the relationships of all the parts (organs) depend fundamentally on information concerning the whole (carried by nervous impulses, chemical signals in the blood, etc.). The concept here (both for an organism and for a quantum system) is that active information actually organizes the parts into a whole, whose behavior cannot be understood by analysis into parts alone.

This implies that wholeness is a basic and irreducible feature of a quantum mechanical universe. Given that this is so, how then do we account for the possibility of the independent behavior seen in common experience and, more generally, in all experience in the classical domain? This is explained by the possibility of factorization of the wave function. Thus, if in the two-body system, we can write $\psi = \phi_A(\vec{X})\, \phi_B(\vec{Y})$, one can readily show that the quantum potential reduces to a sum of independent terms, $Q = Q_A(\vec{X}) + Q_B(\vec{Y})$; $\left(\text{as do also the velocities, } \vec{v}_1 = \frac{\nabla_1 S_A}{m},\ \vec{v}_2 = \frac{\nabla_2 S_B}{m}\right)$. So the two systems behave independently. However, as indicated earlier, this independence is now contingent, in the sense that it depends on special conditions.

But wholeness is the general ground out of which independence may arise as a particular case.

More generally, the quantum information potential may be said to organize all the particles, and to determine the sub-wholes into which they "factorize". As suggested by Baracca et al[16], such sub-wholes may form and break up to re-form later in new ways (rather as domains do in ferromagnetism). In the classical limit, it can be shown that the wave function factorizes to a good degree of approximation and so, relative independence may be expected in this domain. Nevertheless, as we have seen, even here the whole is relevant, in the sense that active information concerning the whole (in the wave function) is what determines both whether or not there is independent behavior, and how far this independence goes. And so, the question of what is a whole and what are the sub-wholes is an intrinsic feature of the quantum state of a system, rather than, as in classical physics, merely one of what is a convenient way to think about a set of particles and to calculate their collective properties.

3. The Quantum Mechanical Process of Measurement

We shall now discuss the process of measurement, as accounted for in terms of the quantum potential interpretation. In doing this, we find it convenient to divide the process into two stages:

(i) Separation of possible states of the quantum system, through an in principle reversible interaction with an apparatus.

(ii) Registration of an actual result of the measurement in a further irreversible interaction.

The first step is usually treated in terms of a spin measurement. However, there is as yet no clearly developed quantum potential interpretation of spin[II] So instead, we shall consider an atom of angular momentum, $\hbar$, which has three internal states, that are functions of the position of an electron variable $(\vec{X})$ with wave functions given by $\psi_n(\vec{X})$, where $n = 1, 0, -1$. We must also take into account the coordinate of the center of mass of the atom, which is denoted by $\vec{y}$. Evidently, the quantum potential interpretation can now be applied in a straightforward way to the 6-dimensional configuration space determined by $\vec{x}$ and $\vec{y}$.

Let us then consider a Stern-Gerlach experiment that will bring about the first stage of separation of the quantum states of the angular momentum through interaction with an

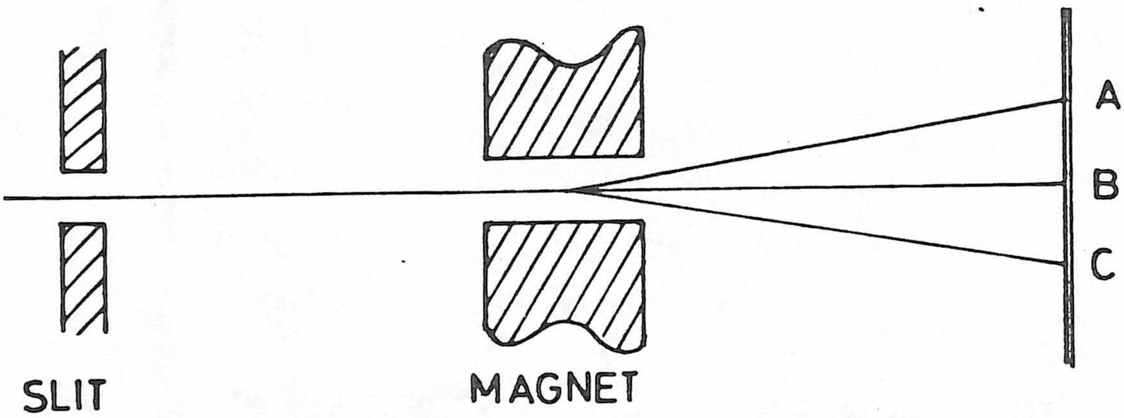

Figure 1

inhomogeneous magnetic field (which is evidently, in principle, reversible). The second stage will then be carried out in the three registration devices, A, B, and C, which will indicate irreversibly what is the actual result of the measurement.

(II) Bell[12] has proposed a simplified model. However, this does not ascribe spin to the particle, but only to the wave packet. Bohm, Schiller and Tiomno[17] have given a model in which the spin properties are ascribed to the particle, but these would lead to complex questions, that would obscure the main points that are relevant here.

We suppose that the wave function of the center of mass is initially a packet, $f_0(\vec{y})$. This packet is physically determined by the slit system and the rest of the experimental arrangement needed to produce a beam of atoms. From the expression for the probability density $|f_0(\vec{y})|^2$, it is clear that the particle has to be within the region in which $|f_0(\vec{y})|^2$ is apreciable, and therefore, one can say that it is located somewhere in the packet.

The combined initial wave function for $\vec{X}$ and $\vec{y}$ is then

$$\Psi_c^0 = \sum_n C_n \psi_n(\vec{X}) f_0(\vec{y}) \tag{9}$$

where the C_n are the (generally unknown) coefficients describing how the various "spin states" are initially combined as the particle comes out of the source.

After interaction with the magnetic field[18], the solution of Schrödinger's equation for $\vec{X}$ and $\vec{y}$ leads to a combined wave function in which the packets separate (as is shown in Fig. 1). This wave function is

$$\Psi_c = \sum_n C_n \psi_n(\vec{X}) f_0(\vec{y} - \xi_n) e^{i\phi_n} \tag{10}$$

where ξ_n is the deviation of the packet, with a Z component of angular momentum corresponding to spin $n\hbar$, and ϕ_n is the phase shift associated with this packet. One can see that if ξ_n is much greater than the width of the packet, $f_0(\vec{y})$, the three parts of the wave function no longer interfere. The probability function for the n^{th} packet is

$$P_n = |C_n|^2 \; |f_0(\vec{y} - \xi_n)|^2 \; |\psi_n(\vec{X})|^2$$

The particle must be in a region in which $|\psi_c|^2$ is appreciable, and so it must be in one of the packets. Once it gets into one of them, it has a negligible probability of crossing the space between the packets (where the probability is essentially zero). And so, the three possible results of the measurement have been clearly separated. Given that $|f_0(\vec{y})|^2$ and $|\psi_n(\vec{X})|^2$ are normalized, it follows that $|C_n|^2$ is the net probability that the particle will find itself somewhere within the n^{th} packet. Hence, from the initial probability distribution $P_0 = |\Psi_c^0(\vec{X},\vec{y})|^2$, and from the action of forces due to the quantum potential, the usual quantum mechanical distribution, $|C_n|^2$, of results of measurements is seen to follow. Moreover, after the packets have separated, it is clear that because they do not overlap, those not containing the particle have no effect on the quantum potential acting in the packet that does contain the particle. We can say, thus, that the particle behaves as if it were solely in <u>one</u> of the possible states. And so, we have accounted for the separation of the possible definite results of a measurement.

There is, however, still a problem. For before registration takes place, we could, in principle deflect the beams reversibly (e.g., by means of another magnet) and cause them to meet, to produce a new "quantum state" that was a linear combination of the three functions, $\psi_n(\vec{X})\, f_0(\vec{y} - \xi_n)$. So, it is possible for the previously described results to become indefinite again in the subsequent process of bringing the packets together. It is therefore clear that we have not yet explained the irrevocability of the experimental results, i.e., that the packets not containing the particle will never have any effect.

This problem is dealt with by considering the second stage, which is the irreversible registration of the result of the measurement in the three devices A, B and C. These pieces of registration apparatus have an enormous number of particles ($\sim 10^{23}$), which we describe collectively by Z_j. Before a given piece of apparatus, A registers it has some initial wave function $\phi_A^0(Z_j)$, so that the three pieces together are described by the product wave function $\phi_A^0(Z_j)\phi_B^0(Z_k)\phi_c^0(Z_n)$.

Now, the experimental arrangement is such that the atom can interact with only one of these pieces of apparatus on any given occasion, while the other two are unaffected. To discuss what happens or we should in principle solve Schrödinger's equation for the total system, including $\vec{X}$, $\vec{y}$, and <u>all three pieces of apparatus</u>, with their coordinates Z_j, starting from the initial total wave function

$$\psi_T^0 = \left[\sum_n C_n \psi_n(\vec{X})\ f(\vec{y} - \xi_n)e^{i\phi_n}\right]\phi_A^0(Z_j)\phi_B^0(Z_k)\phi_C^0(Z_n) \quad (11)$$

Here, we emphasize that although the atom can interact with only one of the registration apparatuses, it is necessary to consider the wave function for a system involving all three of them. This is indeed an example of quantum wholeness, in the sense that even an apparatus that does not function may, in general, be able to make a contribution to the relevant active information content of the over-all quantum potential. So, if we want to show when it does make such a contribution and when it does not, we have to include it in our treatment.

If the atom interacts, say, with apparatus A (which is detecting the particle with spin + ħ), then the wave function of this apparatus /will change to a different one, which we denote by $\phi_A^f(Z_j)$. The wave function of the atom will in general also change. But we can simplify the discussion without loss of essential significance by supposing that its final wave function, $g_t^f(\vec{y})$, is not correlated to the complex movements of the internal coordinates of the apparatus. And, of course, similarly if the particle interacts with apparatus B or with apparatus C.

The final wave function of the total system will then be

$$\psi_T^f = C_1 e^{i\phi_1} g_1^f(\vec{y})\ \phi_A^f(Z_j)\ \phi_B^0(Z_k)\ \phi_c^0(Z_n) \qquad (12)$$

$$+\ C_2 e^{i\phi_2}\ g_2^f(\vec{y})\phi_B^f(Z_j)\ \phi_A^0(Z_k)\ \phi_c^0(Z_n)$$

$$+\ C_3 e^{i\phi_3}\ g_3^f(\vec{y})\ \phi_c^f(Z_j)\ \phi_A^0(Z_k)\ \phi_B^0(Z_n)$$

It is clear that because $g_1^f(\vec{y})$, $g_2^f(\vec{y})$, and $g_3^f(\vec{y})$ still do not overlap, the particle must continue to be in one of these packets (with probability $|C_n|^2$). However, as we have explained earlier, we now have to demonstrate that because of the behavior of the particles constituting the apparatus, even if the different atomic wave packets should overlap in the future, the packets not containing the particle will make no significant contribution to the quantum information potential. This is what will justify their being dropped, and left out of the discussion altogether, from this point on.

Our demonstration that this will happen is based on the notion that the apparatus is a macroscopic thermodynamic system, which is capable of an irreversible process initiated by its interaction with the atom (e.g., as happens in a Geiger counter or an ion chamber). This process ultimately produces a macroscopically observable result, which indicates what the spin of the particle was. Our argument is, in essence, that through collisions and random diffusive processes, a new "quantum state" of the total system was produced which has no significant overlap with the original state, and from which a reversal to anything like the original state would be overwhelmingly improbable.

In principle, it is of course possible for such a reversal to take place, but the probability is so small that this would not be likely, even over the age of the universe (e.g., as unlikely as it is for water placed on ice to boil).

If such an event were to happen in a quantum measurement, it would simply not be recognized as a valid result in physics, because it could not be reproduced (e.g., it could not be distinguished from a mistaken observation). If we accept such an explanation in thermodynamics, it seems that we should also do so here.

To illustrate our argument in more detail, let us consider a simple example. We need a macroscopic source of energy for our apparatus, which is going to be dissipated thermally when a particle is detected, and which will thus permit an irreversible process of registration to take place. Let this energy source be represented by charges on condenser plates. These are to be connected to a piece of apparatus such as an ion chamber

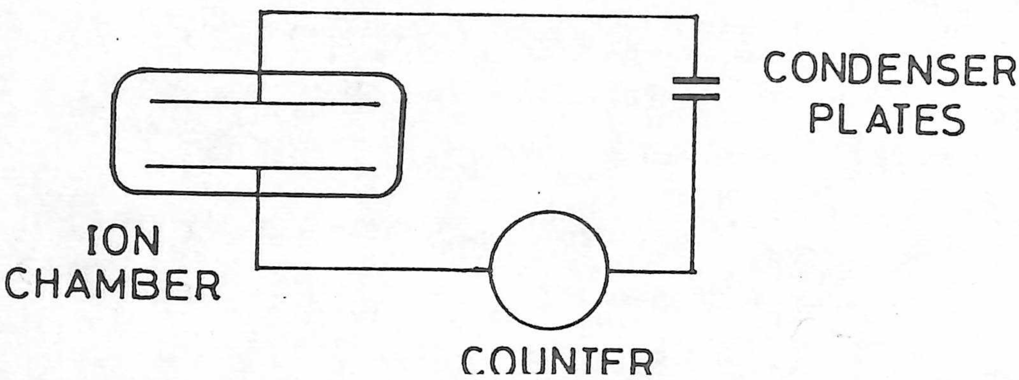

Figure 2

in such a way that if a particle interacts with the apparatus, the stored up energy will be discharged, until equilibrium is established (see Fig. 2). Irreversible changes in the system will thus take place, permitting the presence of the particle to be registered (e.g., by a counter that records each discharge of the condenser).

In the original "quantum state" represented by the wave function $\phi_A^0(Z_j)$, there is a surplus of electrons in one of the condenser plates. In the final "quantum state" represented by $\phi_A^f(Z_j)$ these will have gone to the other plate, to produce a net zero charge on the condenser (or at least one very close to zero). Let us now consider the interference terms $\phi_A^0(Z_j)\phi_A^f(Z_j)$ All the electrons which have gone from one plate to the other will be in regions in the configuration space of the system for which such interference terms are zero (since in $\phi_A^0(Z_j)$ they are on one plate while in $\phi_A^f(Z_j)$, they are on the other plate, which is separated from the first by a macroscopic order of distance). Therefore, when the quantum potential of the whole system is calculated, <u>the apparatus wave function alone</u> will guarantee that the quantum potential reduces to a sum of separate terms, corresponding to the three possible results of measurements. The irreversibility of the process will then further guarantee that <u>in the future</u> the apparatus wave functions corresponding to $\phi_A^f(Z_j)$ and $\phi_A^0(Z_j)$ will not overlap in configuration space. From this, it follows that even if the atomic wave functions $g_n(\vec{y})$ should later happen to overlap, they will still be multiplied by apparatus wave functions which do not. And so, the quantum potential for the particle will also never be affected by the packets not corresponding to the actual result of the measurement.

We are thus led to the conclusion that the packets not containing this particle now correspond to <u>inactive</u> information. This is essentially what happens in classical solutions involving probability distributions. In such situations after a new observation is made, we simply discard the previous probability function. We can always do this classically, because in this domain information is not active. In quantum theory, a further problem has arisen because of the general activity of information in this context. We have solved this problem by showing that through irreversibility in the process of registration, the information in packets not corresponding to the actual result of the measurement ceases to be active, and so can be treated from there on as if it were the kind of information that is in classical probability theory. It is this **change of the character of the information** that is implied (though in a way that is not very clear) by the "collapse" of the wave function.

We have used here an irreversible process based on a discharge of energy stored in condenser plates, which led to a permanent and clear separation of the position of the electrons before and after the process has taken place. As we have already indicated, this was only a convenient illustration. We could have used other processes, such as those involving random diffusion, or radioactivity, to accomplish a similar aim, but this would have been mathematically more complex. However, the principle of irreversibility would work in a similar way.

One may at this stage still wonder whether we could not "undo" the results of the experiment involving condenser plates by means of an external source of energy, which would charge them up again. But then, we would have to include in our discussion the wave function of this source. And, of course, here a similar irreversible process would take place, guaranteeing for the extended total system that there could by no return to the possibility of interference terms that would imply the activity of the information in the packets not corresponding to the actual result of the measurement.

A similar argument can be made for the Schrödinger cat paradox. Here, the wave function will eventually contain a linear superposition of wave functions corresponding to a live cat and to a dead cat. But the cat is (at least initially) a complex living organism, maintained by irreversible processes, which would be very different according to whether the bullet entered it or not. So as with the condenser plates, there will be no interference between these two wave functions, and therefore, the information not corresponding to the actual state of the cat will become inactive, so that it can be dropped from all subsequent discussion (clearly, it would be a miracle if all the parts of the wave function corresponding to a dead cat were to rearrange themselves to produce a wave function that would significantly overlap that of a wave function corresponding to a live cat).

It is clear from the above that the quantum information potential enables us to discuss actuality as independent of the observer (e.g. as in the case of the cat). It can do this because actuality is determined by the movements of the particles constituting a system (which cannot be discussed at all in the usual interpretation). So, it can distinguish between packets that correspond to actuality and those that do not. Indeed, as we have seen, all packets represent information only, and those that can never affect the particle represent inactive information, which has no significance. On the other hand, if, as is the usual interpretation, the wave function represents all that can be said about the system, there is no feature in a wave function covering a number of possible results of a measurement that can represent which of these is the one that is actually present, independently of the activity of an observer. (This is indeed the basis of the Everett interpretation, in which all these results are taken as actual, but each are present in its own special universe to its own special observer.) By showing that the wave function contains active information, parts of which may become inactive through the very laws of development of this information, we are able thus to obtain an in principle unique description of independent actuality.

Our work has a certain relationship to that of Daneri et al[19], who also discuss irreversibility in this context. But our emphasis is on the question of actuality, as made possible by the notion that the electron is a particle, affected in a fundamental way by the quantum information potential implied in the wave function (whereas Daneri et al[19] cannot raise these questions because they discuss it only in terms of the wave function).

Though the wave function in principle combines active information relevant to the whole universe, in typical relations, it factorizes, as we have seen earlier. So beyond certain bounds, the rest of the universe (including the conscious observer) does not matter significantly in discussing specific systems. Of course, if we were to study consciousness itself, as based on the material structure of the brain and nervous system, the question would have to be reopened. Indeed, there are good reasons for expecting that quantum theory, and therfore the notion of a quantum information potential, would be relevant here[20]. Thus, it may well be that in our mental processes, the quantum information potential is significant (as is, for example, suggested by the fact that information regarded as correct is active in determining our behavior, while as soon as it is regarded as incorrect, it ceases to be active). The quantum theory may then play a key part in understanding this domain. But (as has been pointed out earlier) there does not seem to be any strong reason to suppose that the human mind is playing a significant part in the kind of experiments ordinarily done in physics.

Finally, one can see a certain possibility of generalization of these notions. For evidently the definiteness of actual events does not depend necessarily on experiments carried out by physicists in their laboratories. One may reasonably propose that because the entire universe is almost everywhere engaged in irreversible processes, there is a constant tendency for the parts of its wave function not corresponding to actuality to constitute inactive information, which is no longer relevant. So, through irreversibility of development, the universe is able to determine itself spontaneously as being (at least on the larger scale) in definite and unique evolution (in which, it also spontaneously divides into well defined sub-wholes and sub-sub-wholes, etc., along lines that we have discussed earlier in this article). This notion has a certain relationship to the work of Prigogine [21], who, in another context, shows that irreversible processes can give rise to a more or less determinate organization of events and structures in the microscopic level.

4. Non-locality in Field Theory and in Relativity

As pointed out earlier, the quantum information potential has the new feature of non-locality, implying an instantaneous connection between distant particles. This notion is, of course, completely consistent in a non-relativitsic theory. But it has seemed reasonable to suppose that it must violate the laws of relativity theory, especially insofar as these imply that an impulse should not be transmitted faster than light. We shall see, however, that it is possible to extend this interpretation in such a way that the actual implications of relativity for phenomena thus far observable in the context of quantum mechanical statistics are not violated, while at a deeper level, the theory goes beyond relativity.

To do this, we must consider/relativistic form of the current quantum theory. The only known form of this kind is the modern quantum mechanical field theory. We therefore need a quantum information potential interpretation of such a theory.

Such an interpretation was indeed proposed by one of us in an earlier paper [2]. This was done in terms of electromagnetic theory, but we shall simplify the discussion here by using a scalar field instead.

We therefore begin with the scalar field function, $\phi(\vec{x}, t)$, satisfying the equation

$$\Box \phi = 0$$

We now quantize the field equation, introducing an operator

$\Pi(\vec{x}, t) = \frac{\partial}{\partial t}\phi(\vec{x}, t)$, which is canonically conjugate to $\phi(\vec{x}, t)$.

The $\phi(\vec{x}, t)$ and $\Pi(\vec{x}, t)$ constitute a non-denumerably infinite set of operators (one for each point, $\vec{x}$). They operate in what is called a wave functional, $\Psi(\text{---}\ \phi(\vec{x}, t)\ \text{---})$, which may be thought of as a function of all the $\phi(\vec{x}, t)$, over the whole universe. In analogy to the operating relationship, $p\psi = \frac{\hbar}{i}\frac{\partial\psi}{\partial x}$, for a particle, we may write

$$\Pi(\vec{x})\Psi = i\frac{\delta\Psi}{\delta\phi(\vec{x})} \tag{13}$$

where δ represents the functional derivative, operating on Ψ (and where we are for convenience using units in which $\hbar$ and c are 1). As shown in an earlier paper[2], one obtains a "super Schrödinger equation" for Ψ. As is done in the theory of particles, we can then write

$$\Psi = R(\text{---}\ \phi(\vec{x})\ \text{---})\ e^{iS(\text{--}\phi(\vec{x})\text{--})} \tag{14}$$

In going to our new interpretation, the crucial step is to assume that the field function, $\phi(\vec{x})$ is well defined at each time, t, and that it changes in a well defined way.

To determine how the field changes with time we write (in analogy to $m\dot{\vec{x}} = \vec{p} = \frac{\nabla S}{m}$)

$$\frac{\partial\phi}{\partial t}(\vec{x}) = \Pi(\vec{x}) = \frac{\delta S}{\delta\phi(\vec{x})} \tag{15}$$

We can then reduce the "super Schrödinger equation" to a pair of equations, the first representing the conservation of probability, $P = R^2$, while the second is a "super Hamilton-Jacobi equation", for the total field all over the universe. The latter will include in addition to classical terms, the super quantum potential

$$Q = \frac{-\frac{1}{2}\sum'_{(\vec{x})}\frac{\delta^2 R}{(\delta\phi(\vec{x}))^2}}{R} \tag{16}$$

In the above, the symbol, Σ', really refers to an integration, but we have written it as a sum, to bring out the analogy with particle theory.

To complete the interpretation, we have merely to assume that

$$P(\text{---}\ \phi(\vec{x})\ \text{---}) = R^2(\text{---}\ \phi(\vec{x})\ \text{---})$$

is the probability of a certain field configuration for the entire universe, and note that as with the particle theory, the conservation equation guarantees the consistency of this assumption, while further hypothesis of random deviations of the field notions from (15) are able to explain this as an equilibrium distribution.

The wave equation for $\phi(\vec{x}, t)$ then becomes

$$\Box \phi = \frac{\delta Q}{\delta \phi(\vec{x})} \tag{17}$$

In the classical limit, the right-hand term becomes negligible, and we obtain d'Alembert's equation. But more generally, there is a non-local and non-linear addition, due to Q, which can profoundly modify the behavior of the field. This will be treated in more detail as a later paper. But here, we call attention to only a few key features.

Firstly, the entire quantum field may be non-locally connected, so that instantaneous effects may be carried from one point to another that is quite distant. This will explain the quantum properties of fields in a new way. For energies may spread out from one source and then focus on another, as a result of these non-linear non-local terms. Therefore, a quantized field is not intrinsically a collection of individual quanta (i.e., particles). Rather, it is a dynamic structure, organized by the quantum information potential, so that it may give rise to discrete results, though the process itself is not discrete. (It is well known that in other contexts, non-linear equations imply discrete possible structures; e.g., in the case of solitons).

The relevance of this way of interpreting the theory can be seen even more clearly in the case of a light wave that is formed from the interference of beams from two lasers (Pfleegor and Mandel[22]). In the "photon" interpretation, a situation in which there is a single quantum in the whole structure cannot clearly be understood, as it raises the unanswerable question of which laser is the source of the "photon". But in our interpretation, there is no problem, because there are no permanent "photons". There is only a total field activity, organized non-linearly and non-locally by an active information potential, to give rise to the excitation of a single "quantized" transfer of energy to a detector.

This theory implies that even in the vacuum, there is an actual random fluctuation of the field, associated with what is commonly called the zero point energy. This is reminiscent of Dirac's "ether"[23,24]. What are called particles are then actually states of generally conserved forms of excitation of the "ether". The mathematical theory makes it clear that such excitations pass freely through the background without scattering or deviation (as sound waves do in a metal at absolute zero). So, our inability to detect this "ether" by ordinary means is explained.

The question now arises as to the status of relativistic covariance in this theory. In view of the non-local connections, we are forced to assume that this "ether" constitutes a special frame (though one not appearing in ordinary measurements). In this frame, it is consistent to assume instantaneous non-local connections. At first sight, this would seem to violate the requirement of explaining the fact that all known measurements have thus far shown themselves to be comprehended as relativistically invariant. However, measurements that are now possible are described through quantum mechanical operators. It is well known that the quantum mechanical field theory is so consistuted that <u>at the operator level</u> it is relativistically invariant. Moreover, in the earlier papers[1,2], it was shown that in the quantum potential interpretation, the averages of what are now called measurements of quantum mechanical operators are the same as in the usual theory. Therefore, all statistical results of measurements will be invariant. Nevertheless, in individual processes there will be instantaneous non-local connections, in which the "ether" frame is favored. Present statistical observations cannot reveal this frame. To do this would require a level at which the quantum theory breaks down.

As indicated in the introduction to this article, a number of possibilities for such a deeper level have been discussed[3], though it is premature to decide which of the many possibilities might be appropriate here. For the present, the main point that we are emphasizing is, however, that the quantum potential interpretation of a field theory is consistent with all the implications of the theory of relativity that can now be tested and that are now known. The advantage of the quantum potential interpretation is that it permits us to understand how the quantum process actually might work, in, for example, the recent experiment of Aspect et al [13]. Our explanation would be that when the field transfers a discrete quantity of energy to a given detector, the quantum information potential brings about a direct response of the field far away, so that the second detector also absorbs a discrete quantity of energy from the field.

It is worthwhile to go into the point in a bit more detail. Let Figure (3) represent the space-time coordinates in the laboratory frame

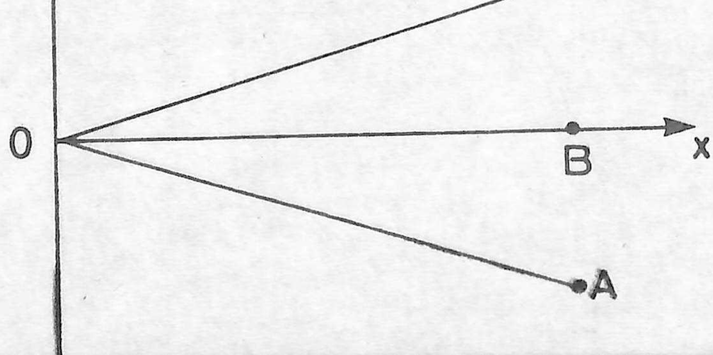

Figure (3)

fig 3

According to the Lorentz transformation, $t' = \frac{t - \frac{Vx}{c^2}}{\sqrt{1-\frac{V^2}{c^2}}}$

$x' = \frac{x-Vt}{\sqrt{1-\frac{V^2}{c^2}}}$, if t' and x' represent the coordinates in the "ether" frame, then lines such as OA and OC will represent constant times in this frame, that correspond to truly simultaneous sets of events. The lines, t = constant, will then evidently correspond to events that are not simultaneous.

Now, the velocity of the laboratory relative to the "ether" is unknown. The line of true simultaneity, t' = constant, will therefore in general be represented by a slanting line such as OC or OA, with slope depending on the unknown speed of the laboratory through the "ether". If this line should happen to be OC, then an action at A which is transmitted instantaneously in the "ether" frame may be connected to C in its future (though, of course, it will still be outside its light cone.) However, if this line happens to correspond to OA, then an action at O could be transmitted to A, in the past of O, as measured in the laboratory frame. But, of course, this does not lead to any paradox. Rather, it may be said that A _is_ actually the true present of O. And it is only because the laboratory clocks are not measuring true time since they are in motion through the ether that they read A as past, relative to O. (Here, we have used the fact that the macroscopic behavior of clocks is adequately described by the statistical treatment of the quantum theory, as applied to their constituent "particles". These are, however, treated as "quantum states" of suitable fields, which, as we have seen, lead to covariant results at this statistical level.)

Finally, it is evident that no _signal_ connecting distant events instantaneously (in the "ether" frame, of course) will be possible, as long as the "measurements" that would detect these signals are limited by the statistical nature of the results of the quantum theory. Thus, fundamentally, relativity and quantum theory are both no longer to be regarded as universal. However, to show this experimentally would require a measurement that would respond at a level at which the quantum theory is no longer valid (so that it could, for example, reveal the presence of the quantum "ether").

5. Summary and Conclusions

The quantum information potential approach is able to deal with all the problems of principle that may be raised both in relativistic and in quantum contexts. It provides an intuitive and imaginative understanding, which gives insight into the new properties of matter implied by the quantum theory. Such insight may help the search for new physical and mathematical ideas, that could take us beyond the limits both of relativity and of quantum theory, as these are now known.

Footnotes

(I) The notion of active information clearly finds an analogue in the field of computer science, for example, in the fact that a programme contains not only passive memory but also instructions that actively guide the computer. Of course, we do not wish to suggest the electron has a computer in it. We are nevertheless calling attention to a considerable similarity of function between the guidance of the electron and the guidance of the computer by active information.

(II) Bell[12] has proposed a simplified model. However, this does not ascribe spin to the particle, but only to the wave packet. Bohm, Schiller and Tiomno[17] have given a model in which the spin properties are ascribed to the particle, but these would lead to complex questions, that would obscure the main points that are relevant here.

REFERENCES

(1) D. Bohm Phys. Rev. 85 166 (1952)

(2) D. Bohm Phys. Rev. 85 180 (1952)

(3) D. Bohm and J.P. Vigier Phys. Rev. 96 208 (1954).

(4) C. Philippidis, D. Bohm and R.D. Kaye Nuovo Cimento 71B 75 (1982)

(5) C. Philippidis, C Dewdney and B.J. Hiley Nuovo Cimento 52B 15 (1979)

(6) C. Dewdney and B.J. Hiley Fond. Phys. 12 27 (1982)

(7) L. de Broglie Une tentative d'interprétation causale et non linéaire de la Mécanique ondulatoire: la théorie de la double solution Gauthier-Villars, Paris (1956)

(8) D. Bohm and B.J. Hiley Fond. Phys. 5 93 (1975)

(9) N. Bohr Atomic Physics and Human Knowledge, Science Editions New York (1961)

(10) E. Wigner The Scientist Speculates ed. I.J. Good, Putnam New York (1965)

(11) H. Everett Rev. Mod. Phys. 29 454 (1957)

(12) J.S. Bell CERN Preprint TH1424 (1971)

(13) A. Aspect, J. Dalibard and G. Roger Phys. Rev. Lett. 49 1804 (1982)

(14) D. Bohm and B.J. Hiley Fond. Phys. 12 1001 (1982)

(15) E. Madelung Zeits. Phys. 40 332 (1926)

(16) A. Baracca, D. Bohm, B.J. Hiley and A.E.G. Stuart Nuovo Cimento 28B 453 (1975)

(17) D. Bohm, R. Shiller and J. Tiomno Nuovo Cimento (Supp.) 1 48, (1955)

(18) D. Bohm Quantum Theory. Chapter 22 Prentice-Hall New Jersey (1960)

(19) A. Daneri, A. Loinger and G.M. Prosperi Nucl. Phys. 44, 297 (1962); Nuovo Cimento 44B 119 (1966)

(20) D. Bohm Ref. 18 Chapter 8.

(21) I. Prigogine From Being to Becoming Freeman,
San Fransisco (1980)

(22) R.L. Pfleegor and L. Mandel Phys. Rev. 159 1084 (1967);
J. Opt. Soc. America 58 946 (1968)

(23) P.A.M. Dirac Nature 168 906 (1951)

(24) B.S. de Witt General Relativity: An Einstein Centenary
Survey ed. S.W. Hawking and W. Israel
Cambridge (1979)